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THE APPLICATION OF HOLOGRAPHY AS A REAL-TIME THREE-DIMENSIONAL MOTION PICTURE CAMERA

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16. ABSTRACT

A historical introduction to holography is presented, as well as a basic description of sideband holography for stationary objects. A brief theoretical development of both time-dependent and time-independent holography is also provided, along with an analytical and intuitive discussion of a unique holographic arrangement which allows the resolution of front surface detail from an object moving at high speeds. As an application of such a system, a real-time three-dimensional motion picture camera system is discussed and the results of a recent demonstration of the world's first true three-dimensional motion picture are given.

17. KEY WORDS

Motion holography
Moving holography
Reflection holography
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HISTORICAL INTRODUCTION

The word "hologram" comes from the Greek words for "holos" and "gram" and means the "entire word" or "whole picture." A hologram does indeed produce the whole picture because it captures all of the information offered by the scene, including parallax and three dimensions. The key to the hologram's performance lies in its ability to record both the amplitude and the relative phase of two separate beams and yet to do this using a recorder which is sensitive to intensity alone.

Holography, which is a method of obtaining a three-dimensional image from a given object, had its beginning in 1948 as a result of the efforts of Dr. Dennis Gabor at the Imperial College of London [1, 2]. Dr. Gabor invented holography, for which he received a 1971 Nobel Prize, in his attempts to improve the resolution of the electron microscope. At first he called it "a new microscope principle." However, this was not the direction holography was subsequently to follow.

In 1950 Dr. Gabor presented a paper on his new microscope principle to the faculty of a small college in Dundee, Scotland. It was there that Dr. Gordon Rogers became intrigued with holography. Both Dr. Gabor and Dr. Rogers were prolific in their achievements in this new field, but because of the limited coherence of the available sources of the day, both utilized Gabor's original in-line holography system. Because of the many disadvantages of that system, interest in holography began to wane. Holography then essentially lay dormant until the advent of the laser with its high intensity and greater coherence length.

It was said of the laser that it was an answer looking for a problem and of holography that it was a problem looking for an answer. The perfect marriage of these two systems was accomplished in 1962 through a suggestion by Dr. Bud Vanderlugt to Dr. Leith and Mr. Juris Upatnieks of the University of Michigan. From their previous experience with coherent radar, they had utilized a local oscillator or separate reference beam to produce RF-type interference patterns; consequently, when they addressed themselves to holography, it was natural for them to insert a beam splitter in the laser beam to obtain a separate reference beam for optical-type interference patterns. Therefore, in 1962 Leith and Upatnieks developed a new type of holography, called sideband holography, which is in vogue in some modified form today.

BASIC DESCRIPTION OF SIDEBAND HOLOGRAPHY

The holographic process which allows the reconstruction of a three-dimensional image is perhaps most simply explained through the use of the Fresnel zone plate analysis. This is a nonmathematical, intuitive discussion which affords the explanation by the use of the zone plate, the diffraction process, and the phenomenon of interference which causes a redistribution of intensity available at the plate. Holography is not discussed from this viewpoint in this report but is available in other literature [3].

The discussion in this report will simply proceed from the holographic arrangement showing the sideband technique. Figure 1 illustrates the sideband technique necessary for the construction of a hologram. Radiation emitted from the laser is amplitude-divided at the beam splitter to form two beams – the reference and the object beams. It is mandatory in holography to use at least two beams. The transmitted beam, which is the reference beam, is turned by a mirror to be incident on the photographic plate. The lens present serves only to enlarge the beam cross section. The wavefront for this beam is undisturbed in its passage from the beam splitter to the photographic plate. One then returns to the beam splitter and traces the second, or object, beam. The beam splitter becomes the reference point for the measurement of the path lengths, of the object and reference beams, from the beam splitter to the photographic plate. Proper use of the coherence length of the laser demands that these path lengths be as nearly equal as possible. The reflected, or object, beam is first turned by a mirror and its cross section enlarged by a lens; it is incident on the object of interest. It is at this point that the wavefront of the object beam is disturbed or modulated. This modulation (which is a change in phase of the object beam) is caused solely by the geometry or three dimensionality of the object being tested.

Since the object- and reference-beam path lengths are equal, both beams reach the plate simultaneously and interfere. Then the plate, responding to the intensity, records or arrests this interference pattern. Although the plate is a square-law detector and, consequently, records only the intensity, it also provides a record of the phase change between the two beams. This is true since the intensity at the plate has been redistributed in a very specific way because of the interference phenomenon, and the very specific intensity distribution present at the plate is caused by the phase of the object beam which has been modulated only by the presence of the object being tested. The three points indicated on the object of Figure 1 should be considered to be extremely small. Radiation from each of these points covers the entire photographic plate. A summation over all such possible points produces the entire solid object. Because light from every possible point of the illuminated object covers the entire plate, the hologram can be broken into slivers, and each sliver will allow the reconstruction of the image of the entire object. After the plate is exposed, it is developed and processed as is any other black and white film. It is then placed back in its original position to reconstruct the image.

The reconstruction technique is shown in Figure 2. The object and the object beam are removed, and the reference beam is incident on the hologram at the same orientation that was used in the reconstruction. The image will appear in the identical position previously occupied by the object. It will be the same size as the object, have the same three dimensions, and afford the same parallax as did the object; in all respects it will be identical to the original object. This is not so surprising because it was the object alone that was responsible for the modulation of the object wavefront, and this modulated wavefront was merely reconstructed.

THEORY OF TIME-DEPENDENT AND TIME-INDEPENDENT HOLOGRAPHY

The equations necessary to describe the holographic process are developed here in an outline form only. The main purpose of such an outline is to demonstrate where the division between time-dependent and time-independent theory occurs and to point out what effect the time-dependent motion has on the holographic exposure. The more complete derivation is available in another report [4].

From the previous diagram (Fig. 1) for the sideband holographic arrangement, let the reference beam be represented by

$$E_r(P) = E_r(x,y)\, e^{i[\omega t - kr(P)]} \quad . \tag{1}$$

Let the scene beam be given by

$$E_s(P) = E_s(x,y)\, e^{i[\omega t - ks(P)]} \quad , \qquad (2)$$

where P denotes some point in the hologram plane. Then the field at the point P of the hologram is that produced by the superposition of both the reference and scene beams and is given by

$$E(P) = E_r(P) + E_s(P) \quad . \qquad (3)$$

The intensity is given by

$$I = m\, E(P)\, E(P)^* \ , \qquad (4)$$

where m is a constant given by $\frac{1}{2}\sqrt{\frac{\epsilon}{\mu}}$. On substitution of equations (1), (2) and (3), the intensity at point P is found to be

$$I = m \Big[E_r^2 + E_s^2 + 2\, E_r\, E_s \cos k \big(s(P) - r(P) \big) \Big] . \qquad (5)$$

To this point nothing has been said about the time dependence, and the development has been general.

The exposure equation is time dependent and is given by

$$\&(P) = \int_{-\tau/2}^{\tau/2} I\, dt \quad . \qquad (6)$$

Further, if one is interested in the transmission amplitude T_a,

$$D = \gamma \log \frac{It}{g} \quad ,$$

$$D \equiv -\log T \quad ,$$

and

$$T = T_a^2 \quad ,$$

therefore, (7)

$$T_a = \frac{1}{g}\,(It)$$

and

$$T_a \propto \& \quad .$$

In order to proceed further, one must specify whether the scene is to move during the hologram exposure. If we allow the possibility that the scene is to move during the exposure of the hologram, then s(P) in equation (5) becomes

$$s(P) = s_p(t) \quad , \qquad (8)$$

and the exposure equation becomes, on substitution of equation (8) into equation (5),

$$\&(P) = m\tau \left[E_r^2 + E_s^2 + \frac{2\, E_r\, E_s}{\tau} \int_{-\tau/2}^{\tau/2} \cos k \big(s(t) - r \big) dt \right] . \qquad (9)$$

Therefore, the time dependence arrives as a result of the phase change of the object beam because of the motion of the object or scene.

Before proceeding further, one must be able to specify s(t) precisely. Consider the object velocity to be linear over some distance s. Then, in general,

$$\frac{ds}{dt} = v \quad ,$$

$$\int_{s_0}^{s} ds = \int_{0}^{\tau} v\, dt \quad , \tag{10}$$

and

$$s(t) = s_0 + v\tau \quad .$$

Substituting equation (10) into the argument of the cosine function of equation (9), one obtains for the exposure or transmission amplitude

$$\mathcal{E}(P) = m\tau \left[K_c + \frac{2\, E_r\, E_s}{\tau} \int_{-\tau/2}^{\tau/2} \cos (kv\tau + \phi)\, dt \right] \quad , \tag{11}$$

where

$$K_c = E_r^{\,2} + E_s^{\,2}$$

and (12)

$$\phi = k\,(s_0 - r) \neq f(t) \quad .$$

After integration, equation (11) becomes

$$\mathcal{E}(P) = m\tau \left(K_c + 2\, E_r\, E_s \operatorname{sinc} kv\, {}^{\tau}\!/_{2} \cos \phi \right) \tag{13}$$

$$\text{where} \ \operatorname{sinc} kv \frac{\tau}{2} = \frac{\sin kv \frac{\tau}{2}}{kv \frac{\tau}{2}} \quad .$$

Note that if $v \equiv 0$, as for a stationary object, then

$$\lim_{x \to 0} \frac{\sin x}{x} = \lim_{x \to 0} \operatorname{sinc} x \equiv 1$$

and the equation for exposure becomes

$$\mathcal{E}(P) = m\tau \left(K_c + 2\, E_r\, E_s \cos \phi \right) \quad . \tag{14}$$

This is precisely what would have been obtained if time dependence had been neglected and equation (5) substituted into the exposure equation (6) earlier.

BASIC DESCRIPTION OF A UNIQUE HOLOGRAPHIC ARRANGEMENT FOR TIME-DEPENDENT HOLOGRAPHY

It has been shown that the time dependence of motion holography is a result of the phase change which occurs in the object-beam path length. It will be recalled that the total optical path length is given by

$$d = n_1\, d_1 + n_2\, d_2 + \ldots = \sum_i n_i\, d_i \tag{15}$$

and, of course, the phase difference between any two points d_1 and d_2 is given by

$$\delta = k(d_2 - d_1)$$

or

$$\delta = \frac{2\pi}{\lambda}\left(\sum_i n_i d_i - \sum_j n_j d_j\right) \tag{16}$$

and

$$\delta = \frac{2\pi}{\lambda}\Delta d \quad ,$$

where Δd is the total change in the optical path length of the object beam during the hologram exposure.

If one is successfully to record a hologram, the total change in the optical path length, Δd, must always be less than $\lambda/2$; i.e.,

$$\Delta d < \lambda/2 \quad . \tag{17}$$

In the holographic arrangement of Figure 3, consider that the motion Δx of the object is along the line of the propagation vector. In this case the target is at position x_0 at the start of the exposure and translates to x_1 by the end of the exposure. The total distance traveled by the object during the exposure is then Δx. The total change in optical path length, Δd, for the object beam is $2\Delta x$; i.e.,

$$\Delta d = 2\Delta x \quad . \tag{18}$$

Yet, using the holographic requirement for recording a hologram, from equation (17),

$$2\Delta x < \lambda/2 \quad . \tag{19}$$

Therefore, for this holographic arrangement,

$$\Delta x < \lambda/4 \quad . \tag{20}$$

The object cannot travel a total distance greater than $\lambda/4$ if a hologram is to be recorded, because the total component of motion has been allowed to cause a change in the object path length in a one-to-one fashion. This was obvious when the object motion was allowed to be along the direction of the light propagation vector k.

It is seen then that the geometry of the holographic arrangement with respect to the object motion vector is extremely critical, as can be further demonstrated by considering Figure 4, where the basic difference from the previous arrangement is that now the motion vector is perpendicular to the propagation vector. The result is, of course, that now Δx may be as large as desired with no corresponding change in optical path length. Then

$$\Delta d \equiv 0 \tag{21}$$

for this arrangement. The price paid for this large motion is that no resolution of front surface detail has been recorded. The image simply appears as a black silhouette against a lighted background.

A geometrical holographic arrangement has been conceived which allows resolution of front surface detail to be recorded in the image, gives maximum utilization of the available coherence length, and, at the same time, allows large enough total motion, Δx, during the exposure to capture any object up to velocities of the order of 34 000 km/hr

(21 000 mph). Such a unique system will now be described.

Consider the ellipse of Figure 5. All three path lengths are the same and are equal to 2a, where a is the length of the semimajor axis. In fact, the distance from one foci to the surface of the ellipse back to the other foci is always constant and equal to 2a.

Suppose we could cause our target to move along the surface of such an ellipse! The laser could then be positioned at one foci and the film recorder at the other. In this way, regardless of the total motion during the hologram exposure, the object path length would always be constant and equal to 2a. However, such a motion trajectory is impossible from a practical point of view. Nevertheless, this situation can be approximated, as shown in Figure 6.

An elliptical holographic arrangement is set up by first calculating the specific values for a, b, and d, where a is the value of the semimajor axis, b is the value of the semiminor axis, and d is the separation distance of the foci from the origin. Allow the motion vector for the object to be tangent to the surface of the ellipse, parallel to the semimajor axis, and perpendicular to the semiminor axis. In this way a straight line approximates the surface of an ellipse. This approximation holds quite well over a small section of the ellipse surface.

Because of the aforementioned constant properties for an ellipse, one can record fairly large object motion during the exposure of a hologram and yet holographically record resolution of front surface detail from the moving object. For the analytical treatment of the properties of such an elliptical arrangement, see Reference 5.

A REAL-TIME THREE-DIMENSIONAL HOLOGRAPHIC MOTION PICTURE CAMERA

By using an elliptical holographic arrangement similar to the one described earlier, we have been able to record and successfully demonstrate a true three-dimensional motion picture taken in real time. The resultant three-dimensional motion picture is, of course, viewable without glasses since the image is truly three dimensional. Perhaps the more significant technical aspects are that the hologram was recorded using a continuous wave laser with a shutter speed of one-sixtieth of a second exposure time, rather than a short-pulse ruby laser, and that the image possessed front surface details, even though the total motion, Δx, of the object during exposure was as high as 700 μm.

The specific system used for recording this first three-dimensional motion, with front surface resolution, is presented schematically in Figure 7. The argon radiation of 514.5 nm (5145 Å) is split by the beam splitter at foci f_1 into the object and reference beams, respectively. The reference beam is spatially filtered and made incident on the 70-mm film position at foci f_2. The object beam is spatially filtered and made incident on the object, which is in continuous motion. It is then scattered and reflected by the object where it is made incident on the film at f_2 and properly interferes with the reference beam. The argon laser operates in the continuous wave mode and is not shuttered; consequently, it constantly illuminates the continuously moving object. For recording the movie, a focal plane shutter is used on the Hulcher 70 film transport. The focal plane shutter consists of a spinning disc with a sector cut out. The sector opening is such that it provides an exposure time of one-sixtieth of a second and allows the recording of 10 frames per second. While the open sector of the shutter is in front of the film, the film is stationary. As the open sector revolves, the film is stepped forward to provide the next frame.

After proper development, the 30.5-m (100-ft) roll of 70-mm film provides the reconstruction of the true three-dimensional image of the object in constant motion. Figure 8 is a schematic for the reconstruction apparatus. At this point no attempt has been made to synchronize the reconstruction radiation with the passage of the hologram frames. Consequently, there is the expected unwanted side motion of the image caused by the motion of the hologram past the reconstruction beam. This, however, is just a detail. The virtual image of the wheel is reconstructed in every detail with three dimensions, parallax, etc., and appears in constant motion, with resolution of front surface detail as expected. However, as further predicted, the amount of detail resolved decreases as the magnitude of total motion during the exposure increases.

Several points should be clarified. First, the use of the film transport is an obvious step and of itself is certainly no innovation. The heart of the technical innovation rests in the taking of the single plate or hologram of the object in continuous motion, under constant illumination. This provided the demonstration of the feasibility of the world's first true three-dimensional motion picture with front surface resolution of detail. Second, this was the first time that an object in motion had been holographically recorded with front surface detail while using a radiation source operating in the continuous wave mode. Certainly, this was the first time this had been done while using a pulse length as long as one-sixtieth of a second! All of these facts of technical performance were allowed only because of the use of elliptical holographic arrangement, with its constancy properties afforded by the classic ellipse.

The actual construction arrangement is shown in Figure 9 and the reconstruction mechanism in Figure 10. Figure 11 is a photograph of the virtual image of the object while it was stationary, and Figure 12 is a photograph of the virtual image of the object while it was in motion at several centimeters per second. Figures 11 and 12 should be compared for the detail lost because of motion versus no motion of the object. Both of these were taken with a 35-mm camera looking through two frames, respectively, of the three-dimensional movie.

The application of the conventional photographic motion picture camera both by the public and by professional societies is all pervasive. It is such a part of our daily activity that its total usefulness is incomprehensible. However, in spite of its total acceptance, it is incapable of displaying to us the real world as we see it. The conventional motion picture is two-dimensional; our real world is three dimensional. If the two-dimensional motion picture camera has such usefulness and total acceptance, we can only speculate on the potential applications of a motion picture camera which displays the world as we know it – in three dimensions!

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812, January 5, 1973
908-52-38-00-00

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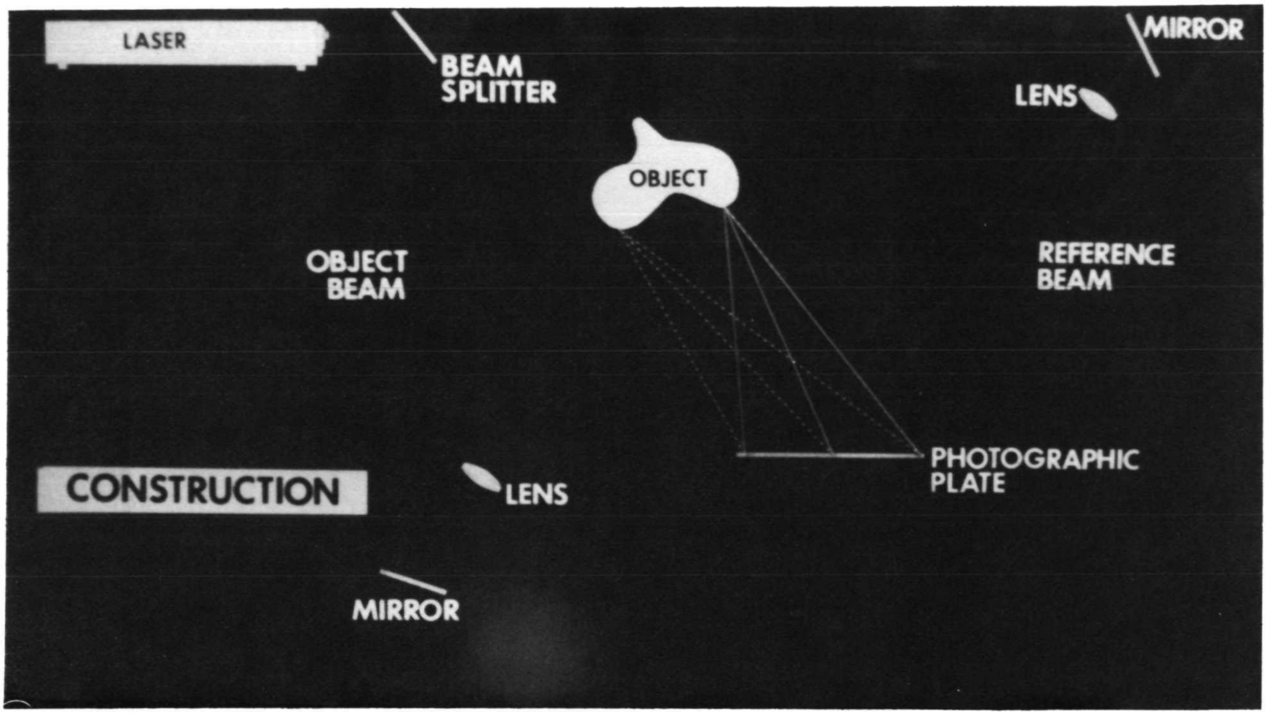


Figure 1. Hologram construction arrangement.

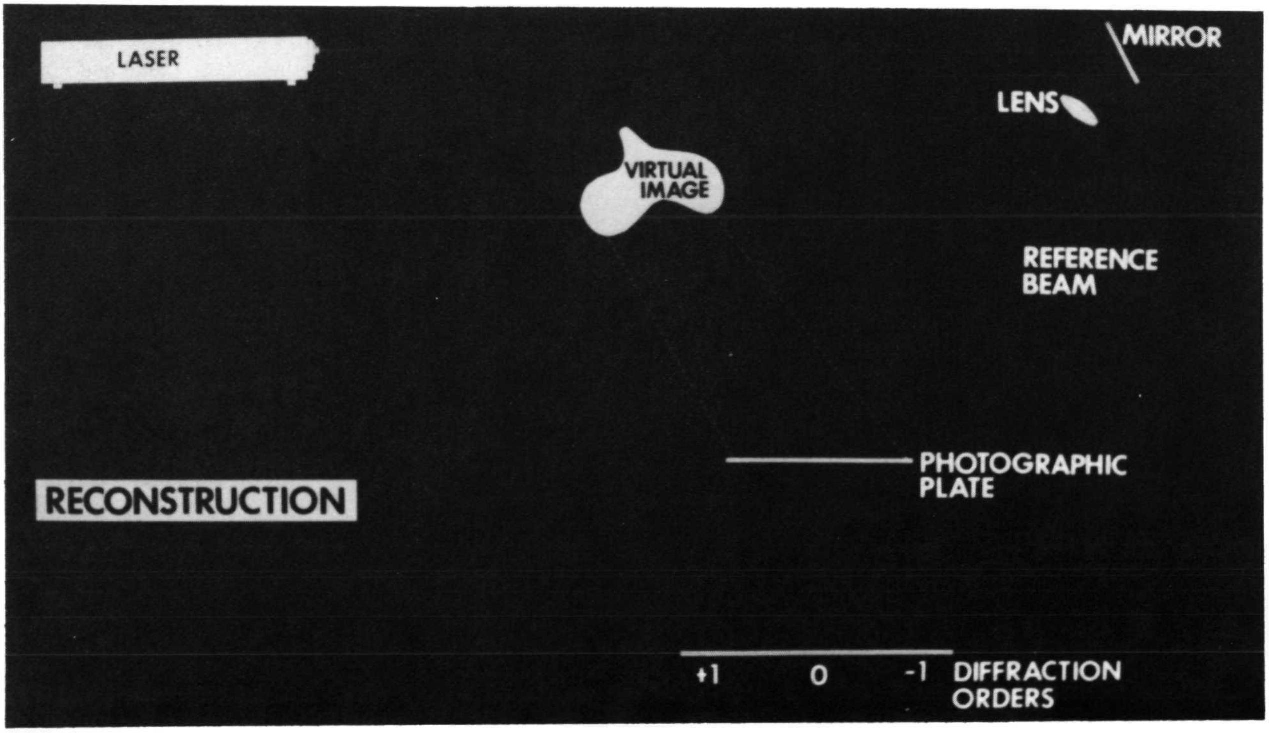


Figure 2. Hologram reconstruction arrangement.

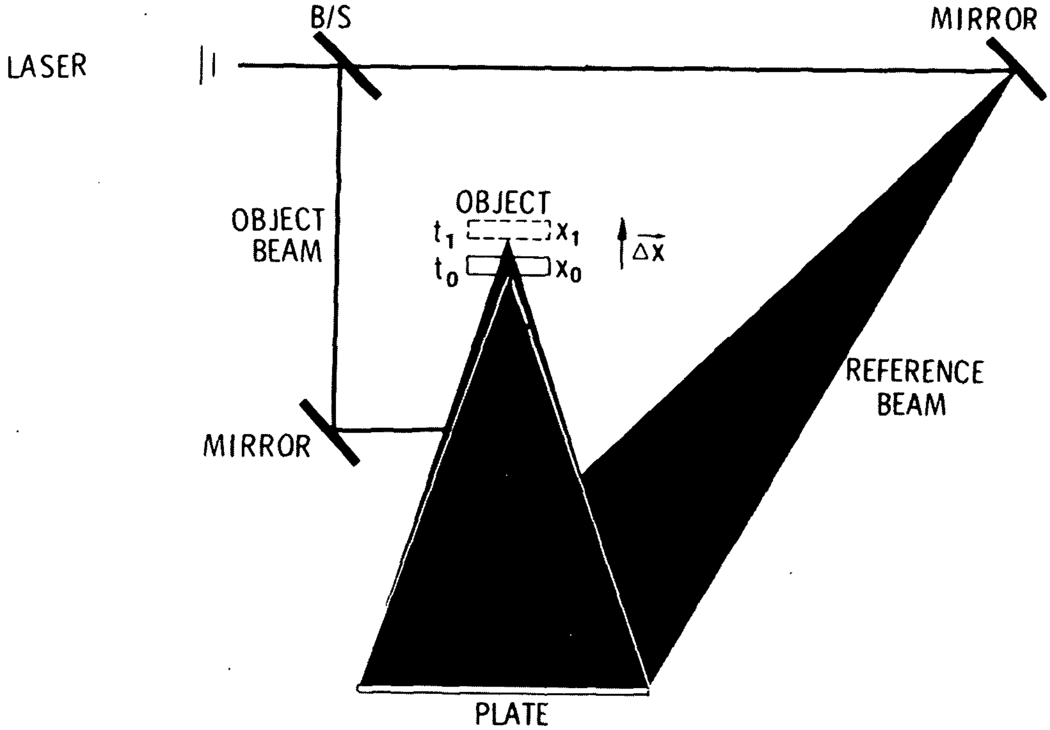
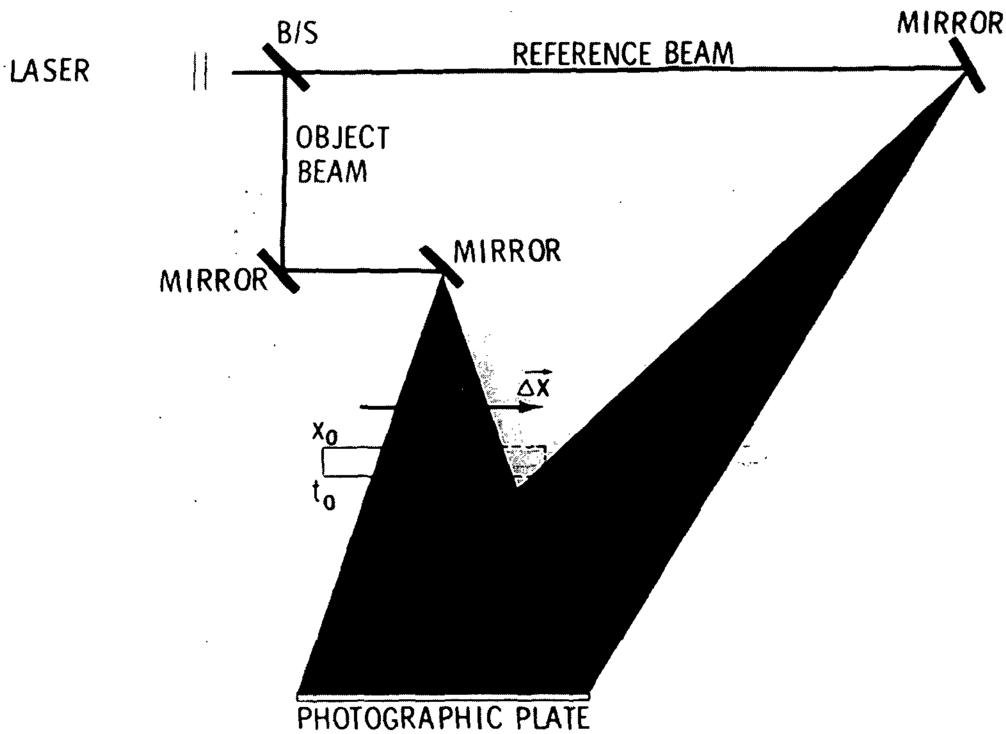


Figure 3. Hologram arrangement for minimum motion.



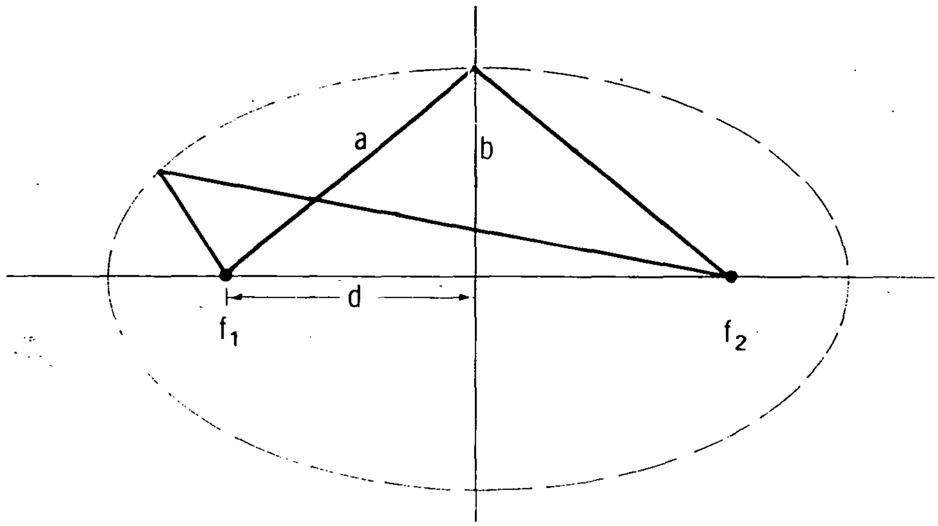


Figure 5. Arrangement of ellipse.

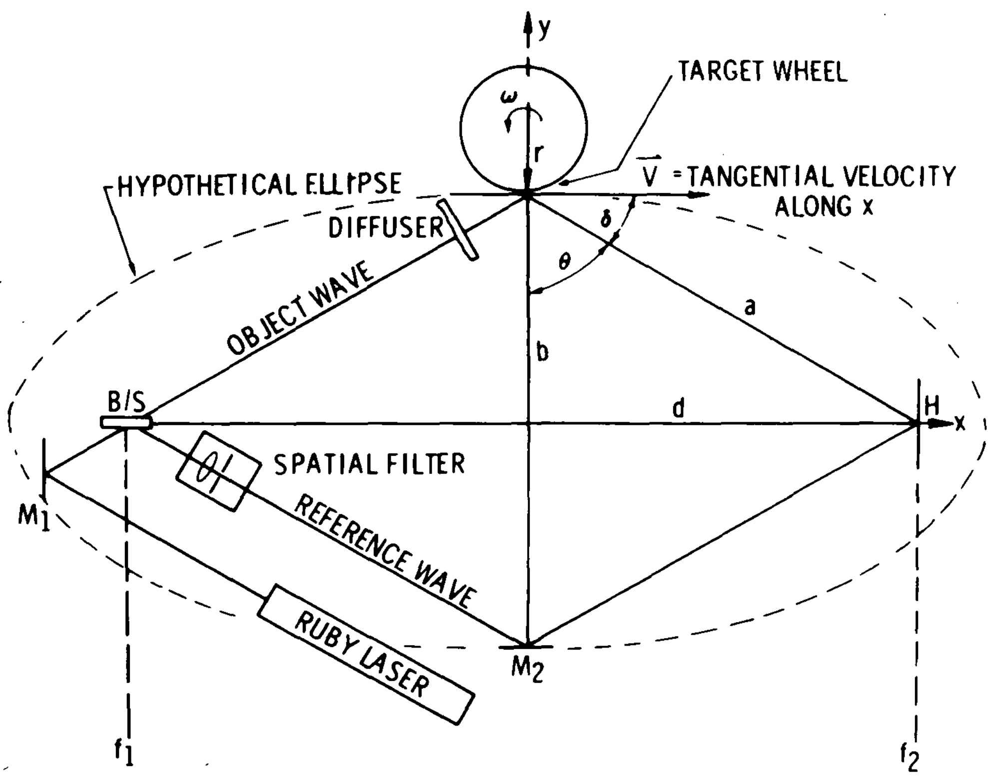


Figure 6. General configuration for elliptical holographic system.

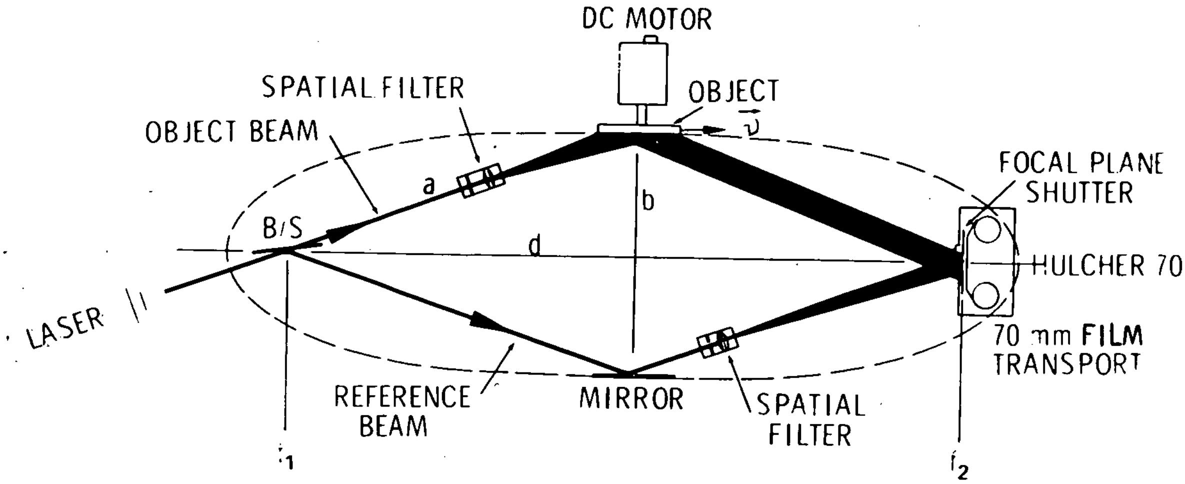


Figure 7. Three-dimensional motion picture arrangement.

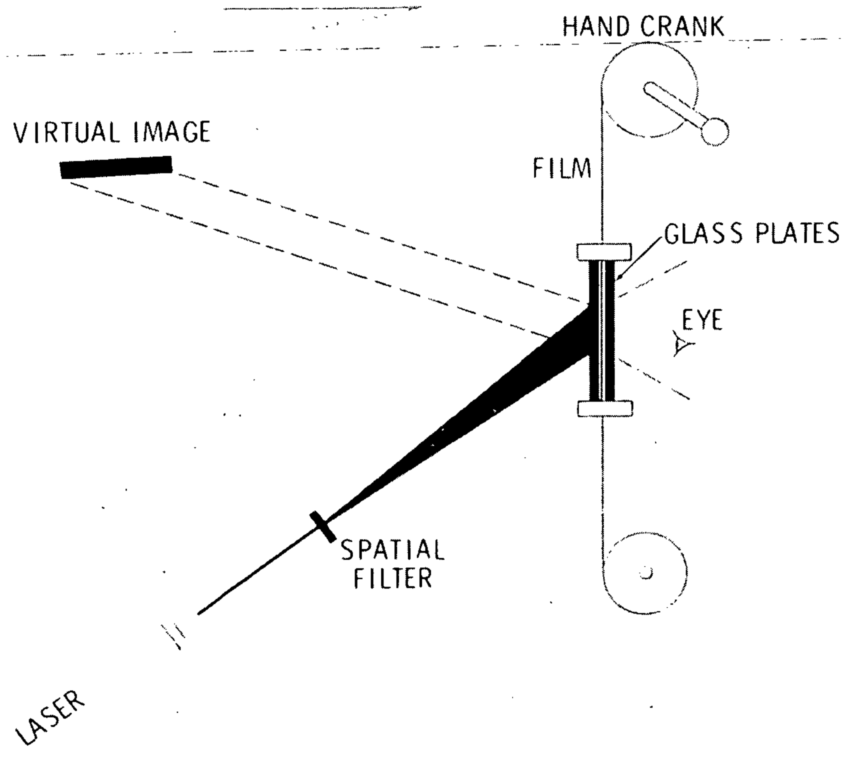
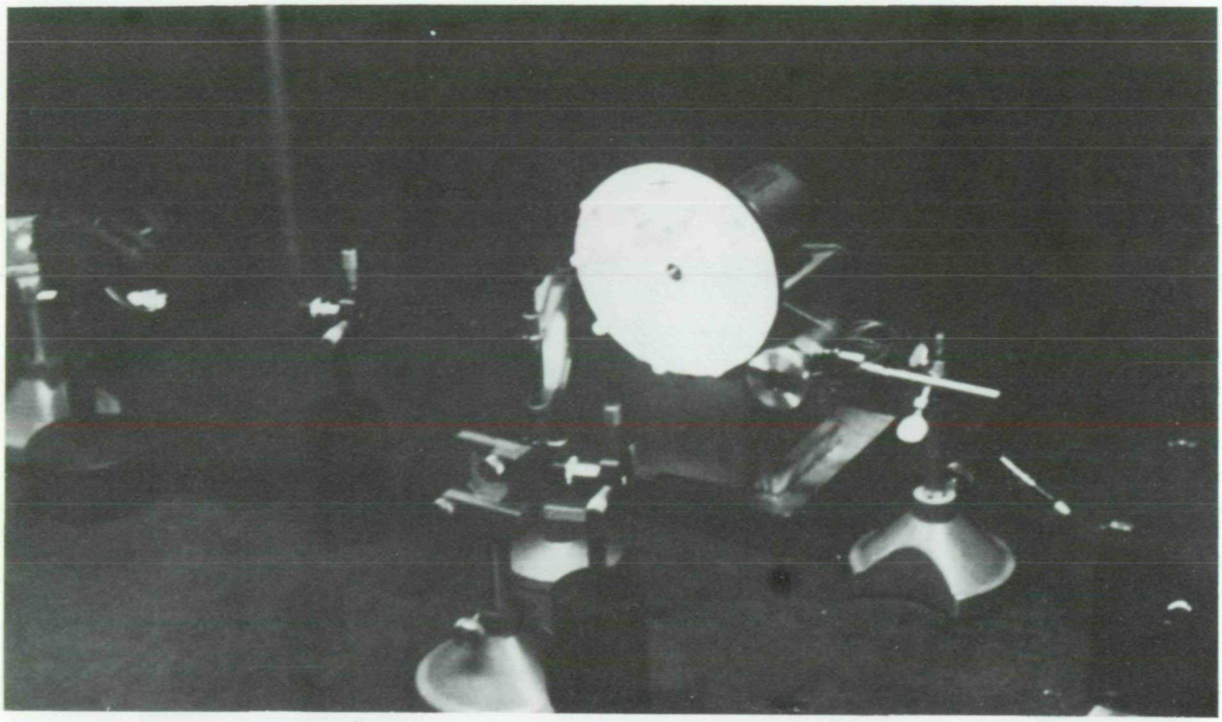


Figure 8. Schematic for reconstruction of three-dimensional movie.



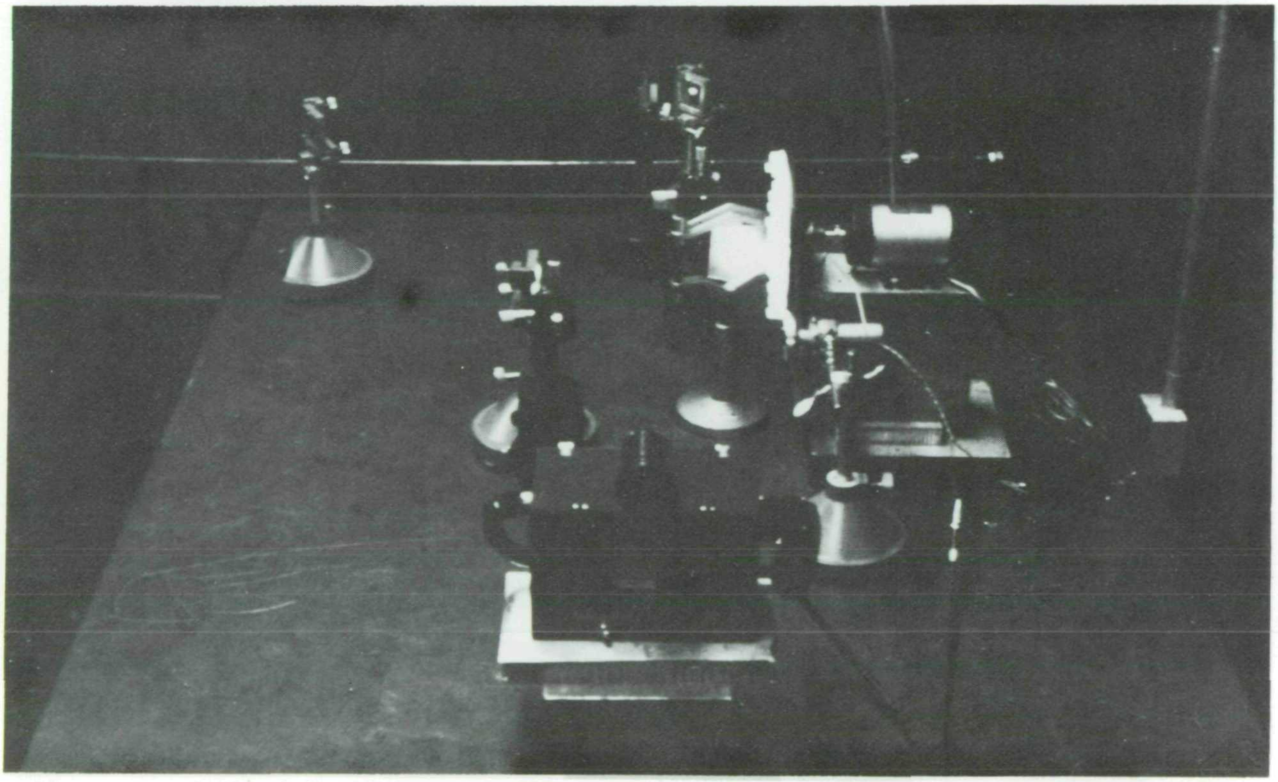


Figure 9. Actual construction arrangement.

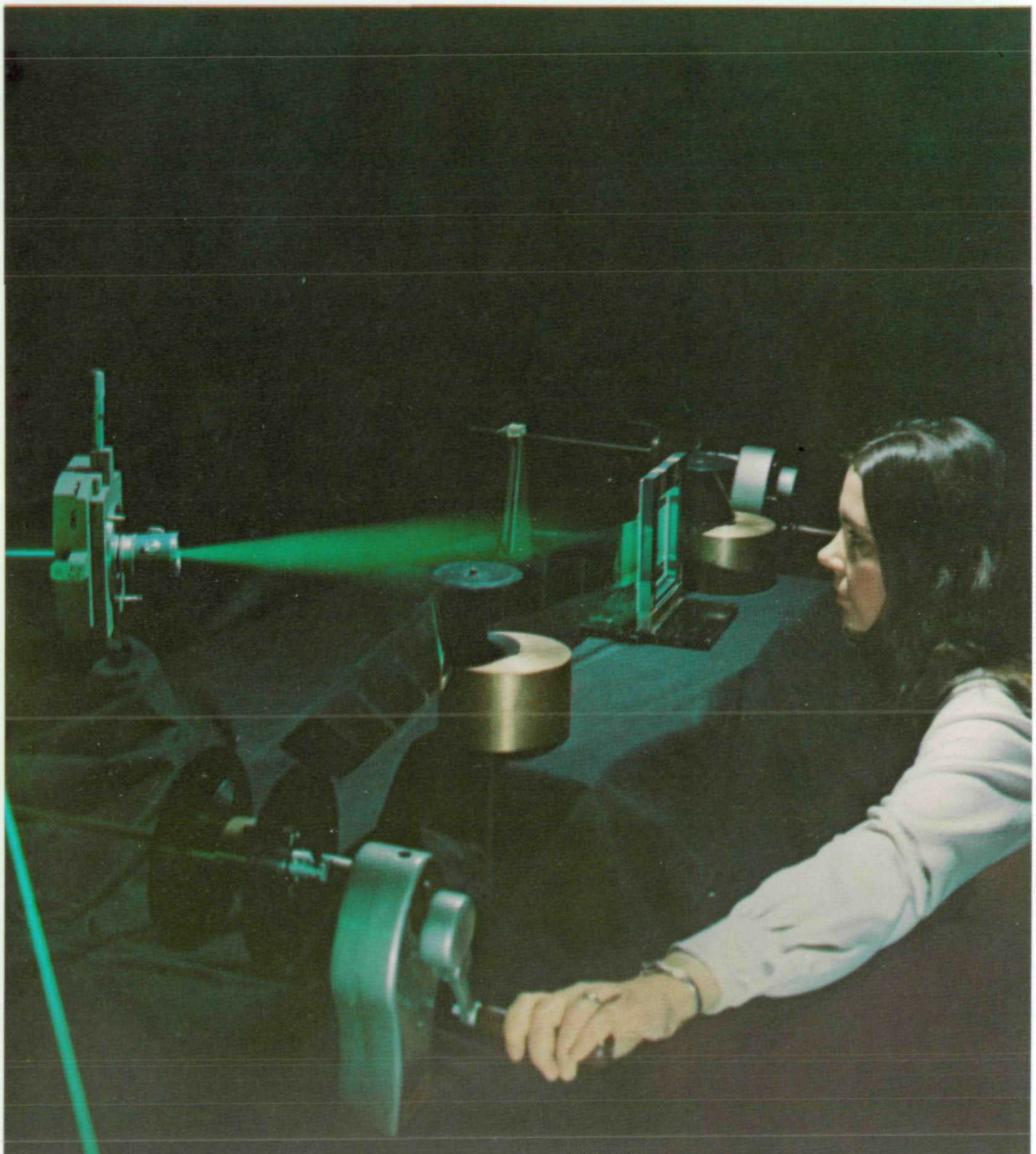


Figure 10. Actual reconstruction arrangement.

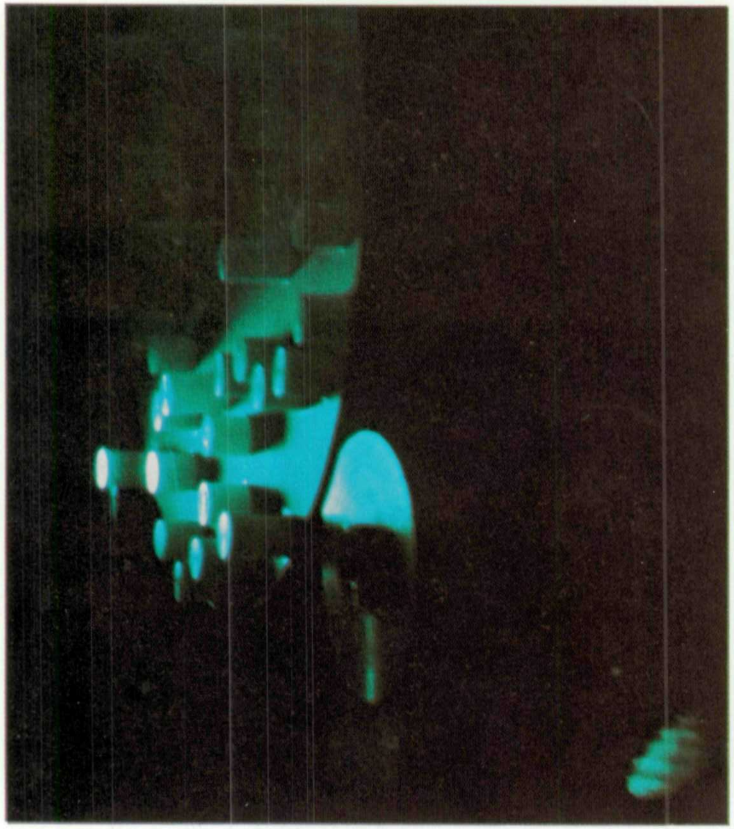


Figure 11. Virtual image of stationary object.

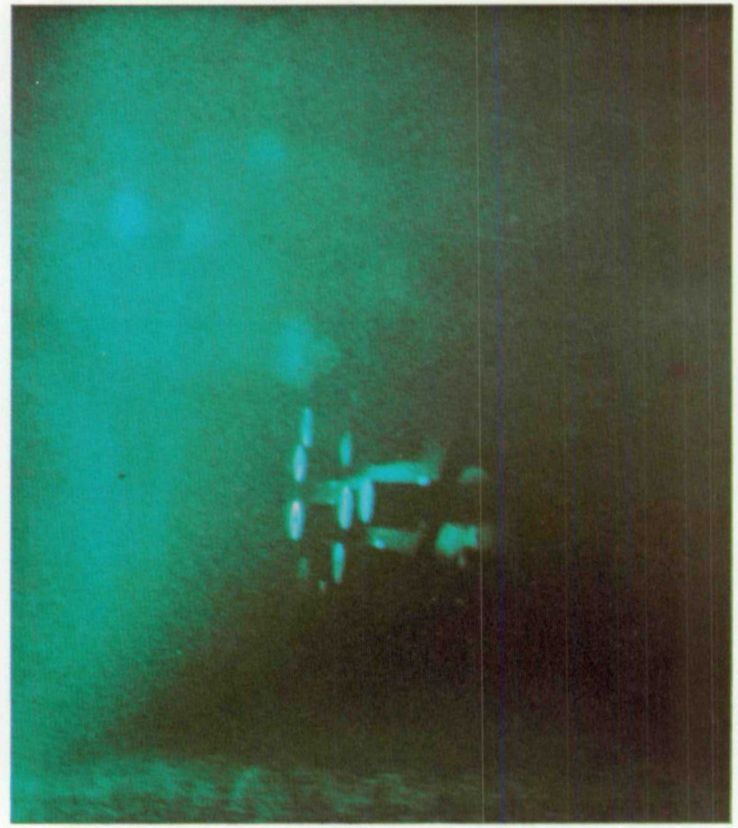


Figure 12. Virtual image of moving object.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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